Double bridge shear testing of sheet metals using 2D micro-DIC

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Abstract. This study presents a novel double-bridge shear testing methodology for characterising in- and out-of-plane shear behaviour of sheet metals, specifically designed to enhance sensitivity to material anisotropy. The method employs a consistent test specimen geometry, enabling direct comparison of shear responses across different material planes, and incorporates 2D micro-Digital Image Correlation (DIC) for high-resolution strain field measurement. A key contribution of this work lies in the detailed analysis of systematic error sources, particularly those arising from manufacturing inaccuracies and loading eccentrices during testing. Specimens were fabricated using high-precision Wire Electrical Discharge Machining (WEDM), and stringent quality control procedures were implemented to eliminate geometrical inconsistencies. The influence of specimen bending—both in-plane and front-back—on DIC accuracy was systematically evaluated and mitigated. The methodology was validated on AW5754-H22 aluminium alloy, revealing through-thickness shear yield stress variation and demonstrating the suitability of the approach for identifying out-of-plane shear parameters of advanced yield criteria such as Yld2004-18p.

Introduction

Advanced characterisation of sheet metals anisotropic plastic behaviour is crucial for reliable metal forming simulations, particularly under multiaxial or shear stress conditions. While traditional tensile and biaxial tests provide valuable in-plane yield surface calibration, their effectiveness diminishes for out-of-plane shear characterisation. Current shear-specific methodologies, such as single-bridge [1] or notched shear tests [2], are prone to issues including shear zone rotation and low sensitivity to shear-related parameters, making accurate parameter extraction challenging. This research introduces a double-bridge shear testing method [3] (Fig. 1a) leveraging a single specimen design adaptable to various material orientations (Fig. 1c). Integrating high-resolution 2D micro-DIC (Fig. 1d), the method provides precise localised strain measurements. Special attention was devoted to identifying, quantifying, and mitigating systematic errors stemming from specimen preparation, loading eccentricity, and testing protocols.

Methodology

Specimen Manufacturing and Quality Control. The double-bridge shear specimens were fabricated from 2.4 mm thick AW5754-H22 aluminium alloy sheets using high-precision Wire Electrical Discharge Machining (WEDM). Given the small geometric features involved—such as fillet radii, shear bridge widths, and ligament dimensions—the WEDM process parameters critically influenced the final specimen quality. The minimum cutting wire diameter used was 0.05mm, with a machine resolution of 50 nm. A clearance of 0.025 to 0.05 mm between the wire and the material was automatically maintained, affecting the minimum reproducible feature size. Preliminary trials revealed that fillet radii below 0.2 mm could not be reliably reproduced. As a result, the shear detail geometry was designed with 0.4 mm per shear bridge, leaving 1.6 mm for the central ligament. Finite Element simulations confirmed that upper and lower ligament widths of 0.5 mm were sufficient to avoid plastic deformation, with the remaining material allocated to the inner ligament. Due to the high sensitivity of the double-bridge configuration to dimensional variations, stringent quality control was essential. All produced specimens were inspected using a Keyence VHX-6000 optical microscope. Ten specimens for each orientation (in-plane and out-of-plane) were sampled. Dimensional parameters including shear bridge length, ligament width, and fillet radii were measured from both sides of each specimen to detect inconsistencies. Only specimens adhering to the nominal design within the acceptable tolerance range were retained for testing.

Identification of Systematic Error Sources. Before tensile testing, a thorough evaluation of potential systematic errors affecting DIC measurement reliability was undertaken. Four key sources were identified: (i) deviations in specimen geometry from manufacturing, (ii) eccentric loading or misalignment during testing, (iii) inconsistent speckle patterning and DIC system setup, and (iv) influence of local crystallographic texture. From a mechanical perspective, two primary bending modes can compromise DIC accuracy: in-plane bending and front-back bending. In-plane bending, caused by misaligned clamping or load eccentricity, leads to asymmetric deformation between upper and lower ligaments. This is detectable via DIC, as it results in noticeable strain differentials between the upper and lower bridges. Front-back bending, on the other hand, creates differential stretching between the front (DIC-facing) and rear surfaces of the specimen, distorting surface strain measurements. Such deformation typically causes out-of-plane movement, resulting in loss of focus in 2D-DIC imagery. Measurements exhibiting either type of bending were excluded from the dataset to preserve measurement integrity. In work of Starman et al. [4], these error sources were analysed in depth. Manufacturing-related geometric imperfections (e.g., asymmetric fillets or bridge widths) were shown to significantly affect strain localisation and force response. However, by enforcing strict specimen selection criteria, these issues were effectively mitigated. Among all sources, front-back bending was found to have the most impairing effect on strain measurement fidelity, particularly in micro-DIC applications.

Experimental Setup and Digital Image Correlation. The specimens were clamped via fixtures designed to minimise bending artefacts while ensuring symmetric loading. 2D micro-DIC was employed using a telecentric lens system to capture high-resolution images of the shear zone. The speckle pattern was applied via airbrushing with optimised contrast and feature size. DIC parameters were tuned to resolve localised strain gradients, particularly near the fillets and ligaments where stress concentrations were expected. The primary metric for evaluating the mechanical response was force–displacement data, supported by virtual extensometers applied to the shear bridge region. Only those measurements where DIC images remained in sharp focus throughout the test were considered valid.

Results

Shear tests conducted in both in-plane (x-z) and out-of-plane (x-z, y-z) orientations demonstrated consistent and repeatable force–displacement behaviour, validating the robustness of the double-bridge specimen design (Fig. 1e). Notably, the out-of-plane specimens exhibited distinct force responses indicative of through-thickness shear anisotropy. The experimental data exhibited high sensitivity to the out-of-plane shear parameters of the Yld2004-18p model, confirming the method’s suitability for inverse parameter identification. The force responses were compared with numerical predictions using a pre-calibrated Yld2004-18p model. In-plane parameters were taken from prior standard tests and literature data [4], while out-of-plane parameters were inversely identified from strain fields using Finite Element Model Updating (FEMU) [5].

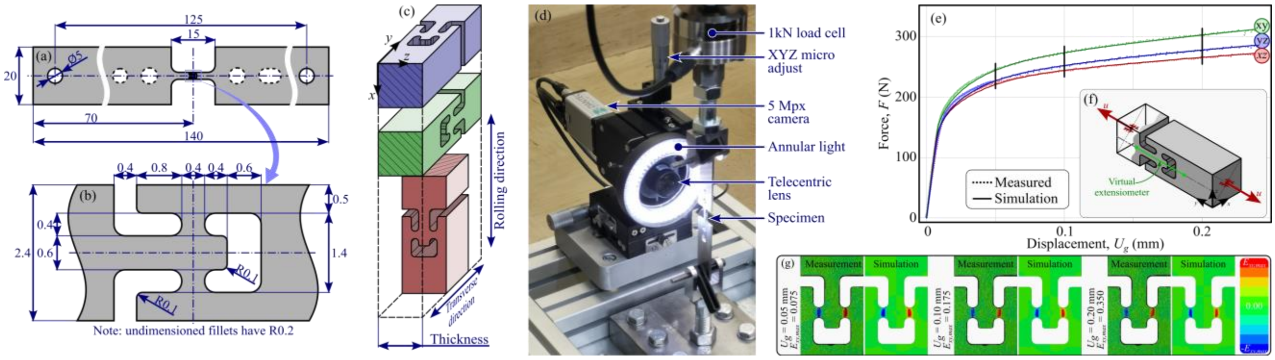

Figure 1. Double bridge shear test configuration and experimental setup: (a) Overall geometry of the shear specimen; (b) detailed view of the shear zone with critical dimensions (all dimensions in mm); (c) schematic representation illustrating different specimen orientations in material planes (x-y, y-z, and x-z); (d) experimental setup with 2D micro-DIC system; (e) comparison of measured and simulated force–displacement responses for different material orientations; (f) schematic illustrating the application of the virtual extensometer to measure effective shear elongation; (g) comparison of shear strain fields.

Conclusion

This work demonstrates that the proposed double-bridge shear testing method, when combined with 2D micro-DIC and rigorous quality control, provides a powerful experimental platform for characterising through-thickness shear behaviour in sheet metals. The approach offers high sensitivity to anisotropic shear parameters, robust handling of systematic error sources, and compatibility with advanced constitutive models.

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